An L-Band Tunnel Diode Oscillator

Report No. 3

Third Quarterly Progress Report

1 December 1962 through 28 February 1963

Contract No. DA36-039 SC-90773
DA Project No. 3A99-21-002

for

U.S. Army Electronics Research
and Development Laboratory
Fort Monmouth, New Jersey

by
RADIO CORPORATION OF AMERICA
Electron Tube Division
Microwave Tube Operations
HARRISON, N. J.

An L-Band Tunnel Diode Oscillator

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The objective of this program is to develop a tunable tunnel-diode oscillator giving 25 milliwatts power output in the frequency range 1660 to 1700 megacycles. The oscillator is to be designed for minimum production cost and shall be adaptable to radiosonde applications.

Contract No. DA36-039 SC-90773

Signal Corps Technical Requirements

No. SCL-7662 Dated 11 December 1961

DA Project No. 3A99-21-002

Report Prepared By
D. E. Nelson
R. Gold
E. T. Casterline

Report Approved By
Frank E. Vaccaro

RCA

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I. The objective of this program is the development of a tunnel-diode oscillator capable of a power output of 25 milliwatts over the tunable frequency range of 1660 to 1700 megacycles. Other requirements include a minimum production cost design, development of solid state modulator circuitry and capability of meeting various environmental requirements.

The program will include the following:

1. Development and fabrication of suitable tunnel diodes.
2. Development of tunable oscillator circuits.
3. Development of modulation techniques and circuits.
4. Testing of tunnel-diode oscillator units to electrical and environmental specifications.
5. Construction for delivery of 1 breadboard oscillator unit, 3 prototype oscillators, 6 developmental model oscillators and 1 breadboard modulator unit.

II. Abstract

A breadboard model oscillator was delivered (Item 3a on the contract).

Tunnel diodes were fabricated from a more highly doped crystal having peak currents of 500 ma with cutoff frequencies in excess of 9 kmc.

Several of the diodes made from the highly doped crystals were tested in stripline oscillators and gave powers of 24 to 28 mw at 1700 Mc.

Preliminary tests were on a tunnel diode current regulator and also on the amplitude modulation of the stripline oscillators.

III. Publications, Lectures, Reports and Conferences

There were no publications, lectures or reports during this report period. The following conference was held:

General Discussion and Review of Contract, January 24, 1963 at RCA Laboratories, Princeton, N. J.

Present: Ivan L. Chase - U.S.A.S.R.D.L.
G. Hambleton - U.S.A.S.R.D.L.
E. McCormick - U.S.A.S.R.D.L.
D. Nelson - RCA Microwave Tube Operations
F. Sterzer - RCA Microwave Tube Operations
F. Vaccaro - RCA Microwave Tube Operations
C. J. Gurwacz - RCA Electron Tube Division
R. H. Siemens - RCA Electron Tube Division

The breadboard oscillator unit (Item 3a under the Contract) was demonstrated and delivered to Mr. Hambleton. The discussion covered general progress under the contract as well as battery requirements, modulation considerations and environmental requirements. It was agreed that RCA will make AM modulation tests using the RCA transistor modulator and that the breadboard unit will be tested with a Signal Corps modulator at the Signal Corps Laboratories.

IV. Factual Data

A. Introduction

The overall effort during this quarter was approximately at the projected rate.

The major effort on the program was directed toward improvement of diodes and the fabrication and test of a breadboard oscillator for delivery under the contract (Item 3a). Other areas receiving attention were circuit development and preliminary amplitude modulation tests.

B. Tunnel Diodes

1. Packaging

The tunnel diodes fabricated during this quarter were mounted in the reduced height strip-line type diode package as described in the previous reports, with two modifications. First, the configuration of the screen used to contact the alloy dot to the top surface of the washer was changed from a strip, which contacted the washer at only 2 points, to a disk large enough to cover the I.D. of the washer and make contact to most of the surface of the washer. Secondly, the screen disk was coated with a layer of conducting silver filled epoxy. These changes should serve to lower the inductance of the unit and increase its mechanical stability.

Twelve units of this type were subjected to a 750 centrifuge test, after which all the units were found to be intact with little or no change at all in their electrical parameters. The value of this technique as far as inductance improvement is concerned has yet to be determined.

2. Diode Development

It was pointed out in the last report that higher I_p/C ratios and therefore higher cutoff frequencies could best be obtained by fabricating tunnel diodes from crystal with an impurity concentration of 8-9 x 10^{19} atoms/cc or higher. Some material of this type has been grown, but it has proved to be extremely hard to reproduce. Most of the crystal available is in the range of 6 x 10^{19} atoms/cc and attempts to fabricate diodes with it have yielded low I_p/C ratios and high series resistance values. In an attempt to increase the impurity concentration to the desired level, a grown GaAs wafer was placed into an evacuated ampoule along with 40mg of Zn. The ampoule was placed in a furnace at 975°C for 18 hours and the Zn allowed to diffuse into the wafer. The initial results were poor, for the surface of the crystal was alloyed with Zn which could not be etched off. It seems that the method of quenching and the size of the ampoule may be important in determining the surface condition after diffusion. Different quenching methods will be studied, and smaller ampoules will also be evaluated.

From the equation for the cutoff frequency:

$$f_{co} = \frac{1}{2\pi RC}\sqrt{\frac{R}{r_s} - 1}$$

where R is the diode negative resistance, r_s is the series resistance and C is the junction capacitance, it can be seen that decreasing the series resistance will increase f_{co}. Thus, an attempt was made to reduce the series resistance of the units made with the material on hand to a minimum. One method employed was the etching of a hole in the pellet on the opposite side of the junction (see Figure 1) and then alloying a metal into it. Since the resistance of a metal is less than that of a semiconductor, the resistance through the unit should be less. This method failed to produce any noticeable difference in r_s.

Lapping the wafers very thin, $\sim$1.5 mil, before alloying and processing has given lower initial values of r_s, .15 ohm for 1.5 mil crystal vs .165 ohm for 3 mil thick crystal, but there does not seem to be much difference after the units are etched.

Another approach used was to place a layer of nickel and gold on the top surface of the pellet very close to the contact dot so that the distance from the contact dot to the gold layer is less than the thickness of the wafer (see Figure 2). If contact is then made between the dot and the gold layer the resistance should be less than if contact was made, as usual, through the wafer to the back of the pellet, particularly at microwave frequencies.

Results were poor due to peeling of the film and difficulty in making a good ohmic contact to the pellet surface. Although good contacts probably could be made to the top, it is not certain that there would be any distinct advantage to such a geometry. This is because the skin depth at 2 kmc is about 10 mils, whereas typical semiconductor pellets are only 1 mil thick. Because of the greater importance of obtaining an adequate supply of highly doped crystal, this approach will not be pursued further.

The 2nd Quarterly Report discussed the variation of f_{co} as the diode is etched to produce a desired peak current. During this quarter, this variation was investigated for the crystal used for fabricating the microwave tunnel diodes. Three diodes, having approximately the same initial Ip (950 ma), which had been fabricated from the same crystal were etched to 25 ma in small increments and the diode parameters were measured at each increment. The results are plotted in Figure 3. In the electrolytic etch process, Ip decreases directly with the area, while the series resistance r_s increases inversely with the square root of the area. Then as Ip is decreased, the product of Ip r_s also decreases and the f_{co} must increase. Figure 3 shows this to be true, for as each of the units is etched, the cutoff-frequency increases. It is interesting to note that each of the units exhibits a maximum at 150 ma Ip. The reason for this is not quite clear, but is being studied further.

It must be pointed out that the tunnel diodes selected for this test were fabricated from crystal whose impurity concentration was in the range of 8.0×10^{19} atoms/cc but whose initial Ip values were somewhat lower than that normally used for 600 ma diodes. This was done deliberately since the measurement of units with Ip's greater than 900 ma in our present capacitance test set will most likely damage it.

The results indicated in Figure 3 point out the possibility of shifting the maximum f_{co} point to the 600 ma level through the use of the proper combination of material and alloying cycle. This is precisely what we attempt to do when fabricating units of that type.

During this quarter, 25 tunnel diodes were produced for circuit evaluation and testing. Of these, five had superior electrical characteristics due to the high doping level ($\approx 8 \times 10^{19}$ atoms/cm^3) of the starting crystal and the use of an optimum alloy cycle (to produce a very high current density). Cutoff frequency for three of these diodes (Ip = 500 ma) was greater than 9 kmc. Several of these diodes gave power outputs of 24 to 28 milliwatts at 1700 mc. This represents a marked improvement over previous results (17 mw at 1680 mc).

C. Oscillator Circuit Investigation

A breadboard oscillator, SS116 Serial No. 001, was fabricated, tested and delivered as item 3a under the contract. The oscillator employed a circular reentrant stripline circuit. A sketch of the circuit is shown in Figure 4. Tuning was accomplished by means of 10 pf variable condenser. The tunnel diode was a gallium-arsenide stripline package unit having the following characteristics

Peak Current	445 ma.
Series Resistance	0.3 ohms
Capacitance	29 p.f.

Curves of power output and frequency of the oscillator versus tuner turns are shown in Figure 5. Similar curves versus bias voltage are given in Figure 6. The pulling figure of the oscillator at a 1.5 VSWR was 47 Mc. A 10 db isolator placed at the output of the oscillator, reduced this value to 7 Mc.

The five diodes made from a crystal doped to a higher level, discussed at the end of Section IV B-2, were tested in a reentrant stripline oscillator circuit similar to that of Figure 4. The three diodes having peak currents of 500 ma were very consistent, giving power outputs of about 25 mw at about 1700 Mc. The 510 ma and 400 ma peak current diodes were lower in both power output and frequency of operation. The reason for this is not obvious from the diode characteristics. The characteristics and test results are tabulated below.

Table I

Tunnel Diode				Bias		Power Output mw	Freq. Mc	Impedance Matcher
Serial No.	Peak Current ma	C pf	Cutoff Freq. Gc.	mv.	ma			
485-1	500	30	7.4	580	1800	23	1690	No
				580	1830	26	1726	Yes
485-2	510	36	9.5	490	1160	18	1531	No
				485	1170	21	1576	Yes
485-10	500	20	11.0	515	1250	26	1625	No
				540	1250	28	1735	Yes
346-18	500	39	9.9	575	1270	22	1520	No
				565	1270	24	1710	Yes
485-9	400	26	6.9	455	1230	15	1583	No
				475	1260	16	1632	Yes

The revised quarter-wave coaxial oscillator described in the Second Quarterly Progress Report was fabricated and tested. The frequency of operation was below 1000 Mc and the power output less than 1 mw. This is believed to be due to the bias input circuit; however, due to the promising results with stripline oscillators, further work on the coaxial oscillator will be given low priority.

D. Power Supply and Modulator Circuitry

Preliminary tests were made of a current regulator consisting of a low speed germanium tunnel diode with a stabilising resistor painted on the outside of the diode package. This combination gives a flat current versus voltage characteristic over a voltage range of 100 to 150 mv. It is connected in series with the tunnel diode oscillator and thus reduces the voltage variation appearing across the oscillator when the bias supply voltage is varied. When tested with a TD oscillator the regulator reduced the frequency variation of the oscillator due to a ± 5% bias voltage variation from 30 Mc to 4 Mc. There was modulation of the oscillator, however, due to low frequency oscillations of the regulator. A simple filter eliminated much of the modulation but some modulation still remained at certain values of bias voltage. Further work is required to increase the [illegible] of the regulator and to eliminate the remaining modulation.

The transistor blocking oscillator modulator described in the First Quarterly Report was used to modulate a TD oscillator. The oscillator was operated at a peak power of 15 mw and a frequency of 1670 Mc. The pulse width of the modulator was 33 microseconds. The modulator required an input voltage of 12 volts and the current input varied from 100 ma at 575 p.p.s. pulse repetition rate to 500 ma at 8300 p.p.s. The control resistance which determines the pulse repetition rate was 15,000 ohms for 575 pps and 0 ohms at 8300 pps. Figure 7a shows the waveform of the modulator output and Figure 7b that of the rectified output of the tunnel diode oscillator. The rf spectrum of the oscillator is shown in Figure 7c. In general the results seem reasonably promising except for the control resistance range of the modulater which is much lower than desired.

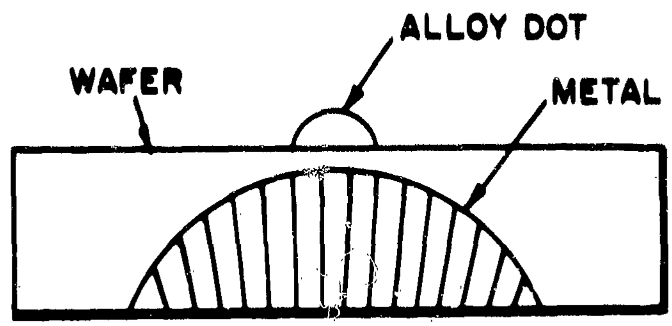


FIG. 1 REVERSE ETCHED DIODE

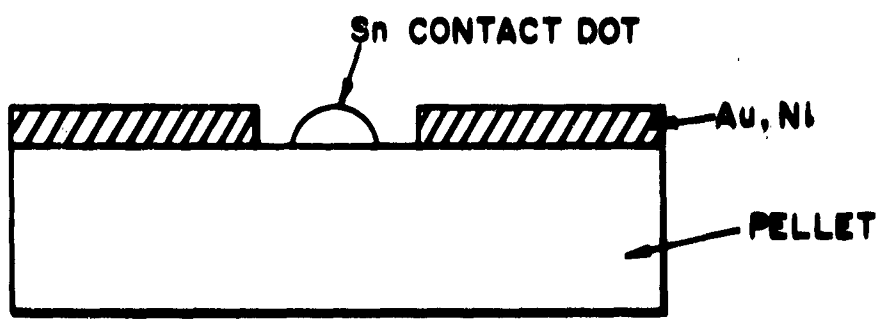


FIG. 2 GOLD COATED PELLET

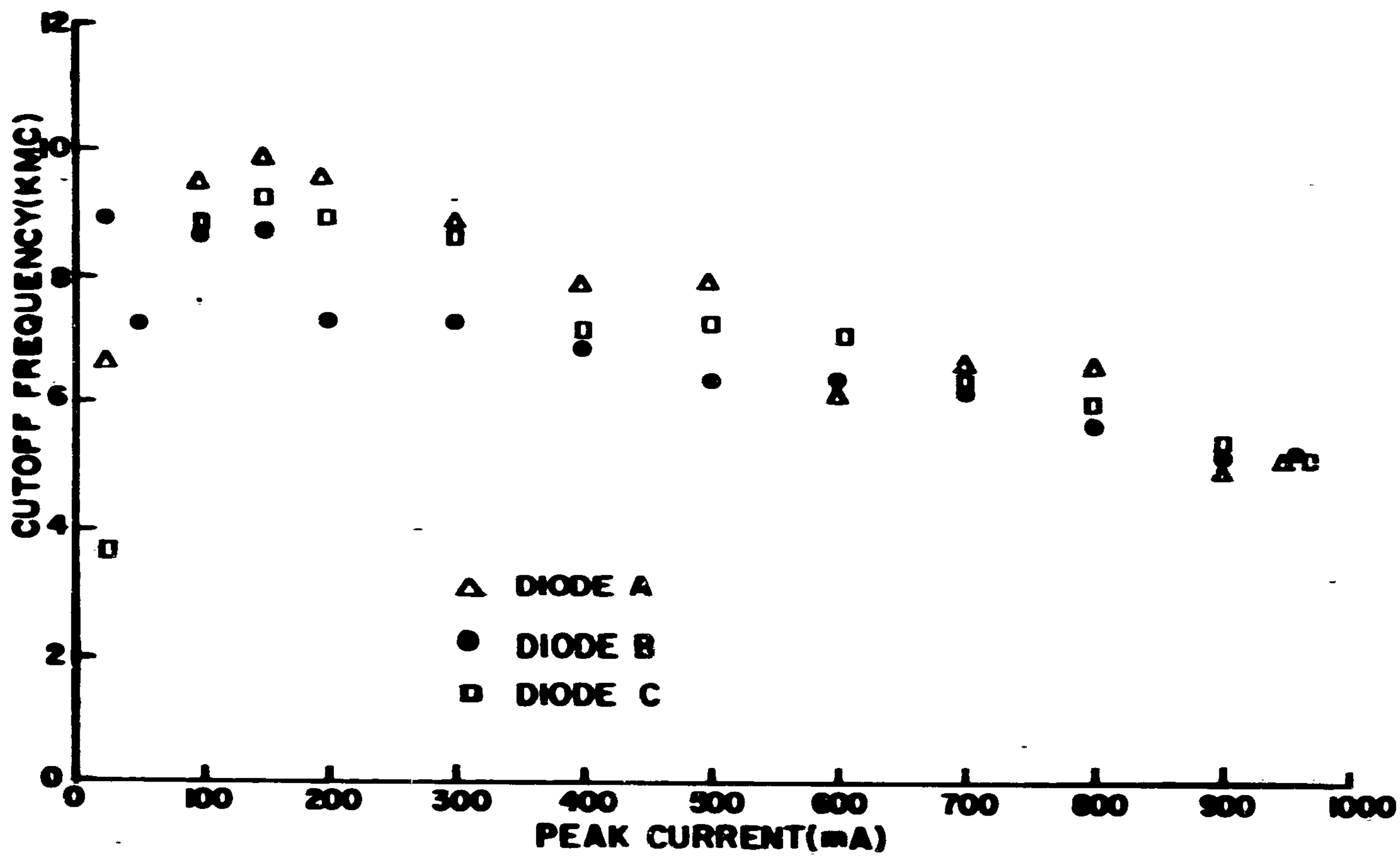


FIG. 3 CUTOFF FREQUENCY vs. PEAK CURRENT

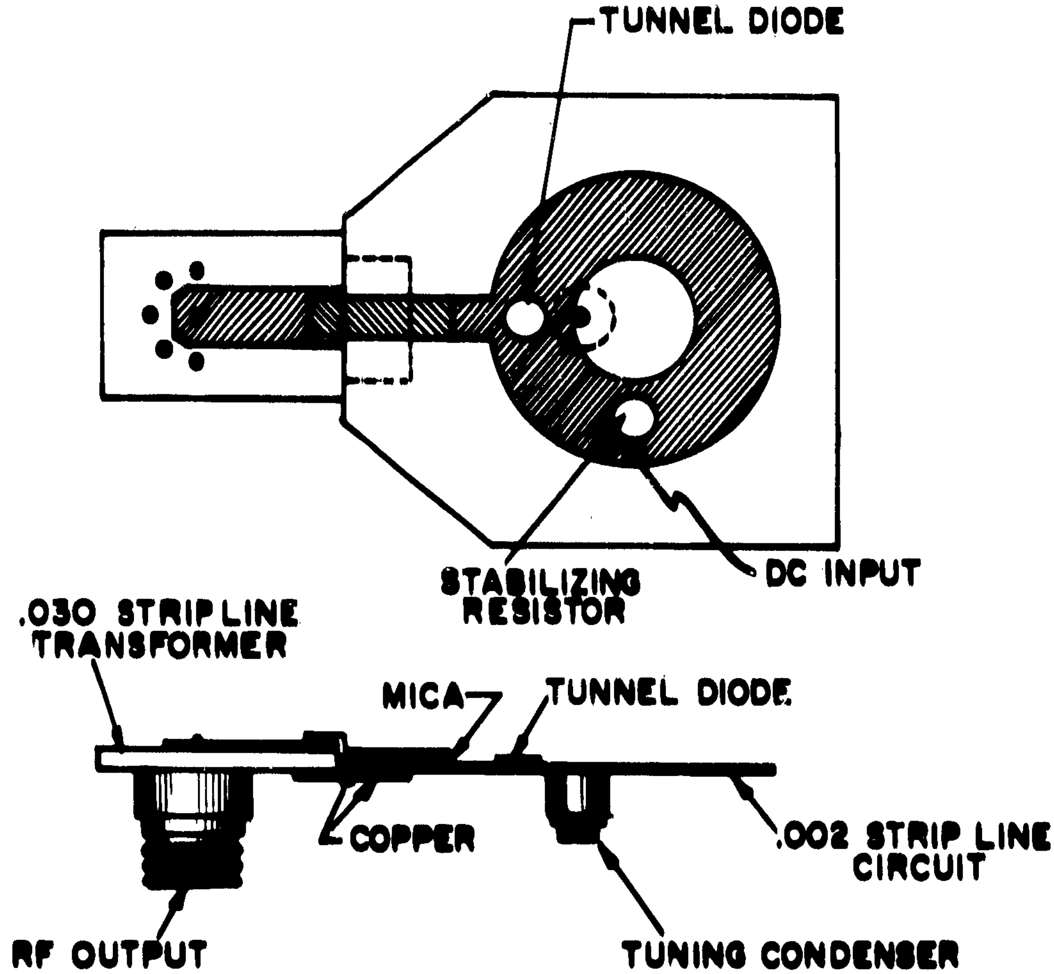


FIG. 4 CIRCUIT FOR BREADBOARD MODEL OSCILLATOR SS 116 SER. NO. 001

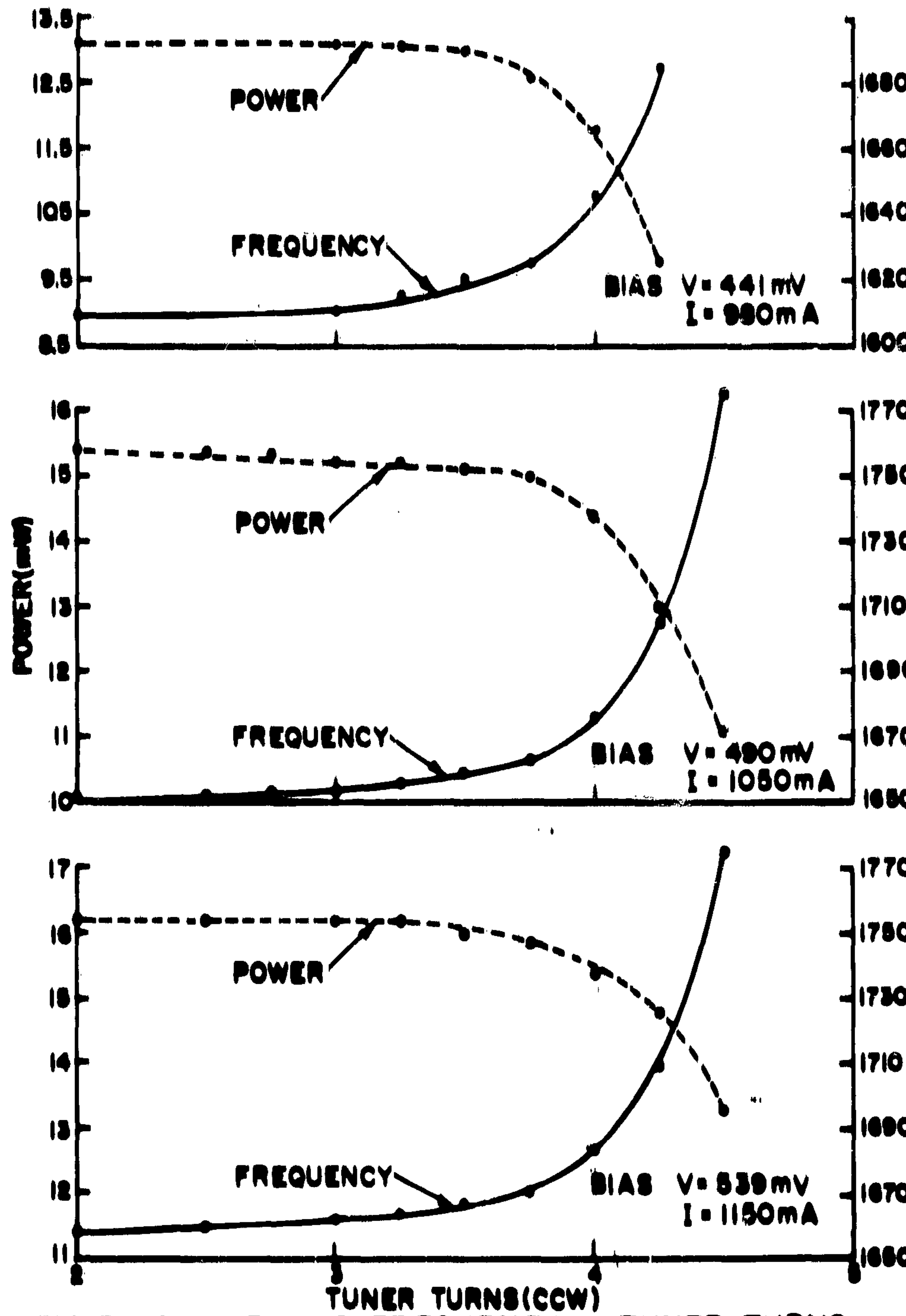


FIG. 5 POWER AND FREQUENCY vs. TUNER TURNS (SS116 SER. NO. 001)

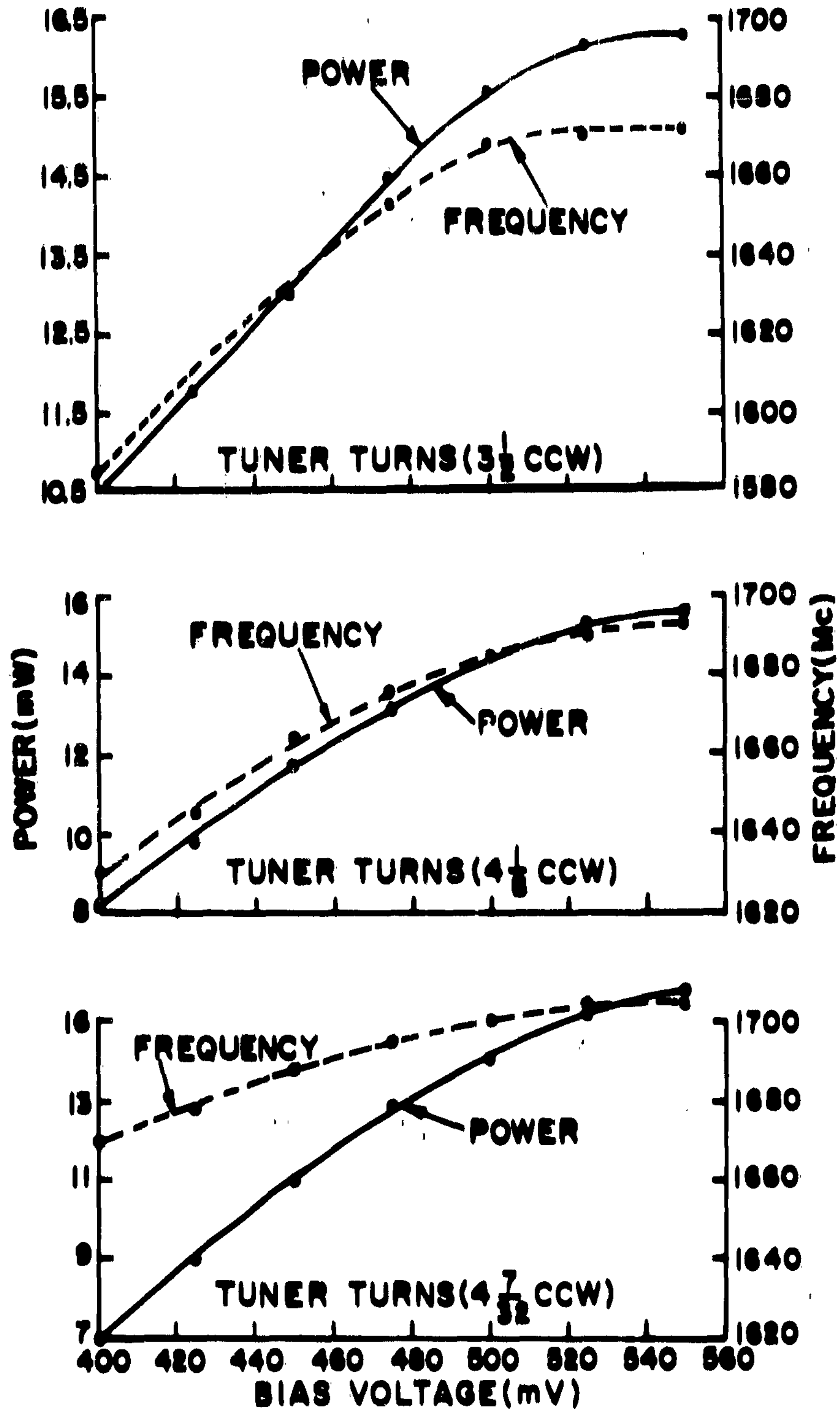
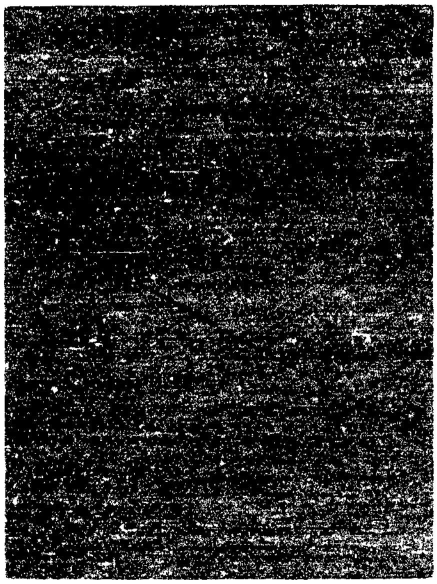
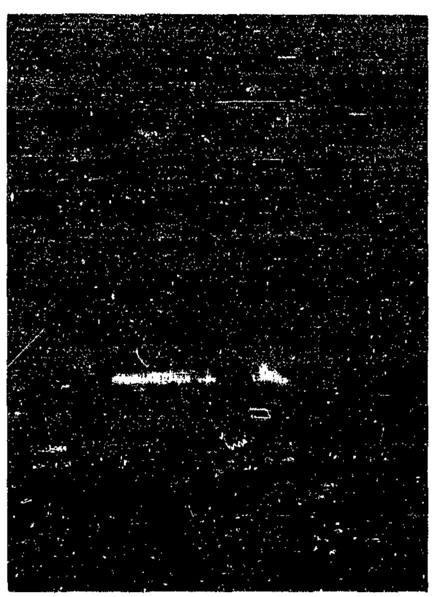


FIG.6 POWER AND FREQUENCY vs. BIAS
(SS116 SER. NO. 001)



(a) OUTPUT OF MODULATOR HORIZONTAL SCALE 20μ SEC/CM

(b) RECTIFIED OUTPUT OF TD OSCILLATOR HORIZONTAL SCALE 20μ SEC/CM



(c) RF SPECTRUM OF TD OSCILLATOR HORIZONTAL SCALE 90 KC/CM

FIG. 7 MODULATOR WAVEFORMS

V. Conclusions

Efforts to increase the cutoff frequency of 500 ma peak current gallium arsenide tunnel diodes through reduction of series resistance, have been unsuccessful to date. However, through the use of highly doped crystals (8×10^{19} atoms/cm^3) a number of 500 ma diodes have been made with cutoff frequencies greater than 9 KMC.

Power outputs of 24 to 28 mw at 1700 Mc were obtained from these diodes operated in reentrant ring stripline circuits.

A breadboard model oscillator (item 3a under the contract) was delivered. The oscillator gave a power output of 13 to 16 mw over the required 1660 to 1700 Mc tuning range.

Preliminary tests were made on the use of a tunnel diode current regulator to reduce oscillator frequency changes as the bias was varied. The method is promising although further improvement is required.

A tunnel diode oscillator was amplitude modulated using the transistor modulator described in the First Quarterly Progress Report.

VI Program for Next Interval

Techniques for increasing diode cutoff frequency and self-resonant frequency will be investigated further.

The study of diffusion methods for obtaining highly doped crystal will be continued.

Tests of stripline oscillator circuits will be continued and the design of output circuits to reduce frequency pulling will be investigated.

Use of nonlinear stabilizing resistors to reduce the dc power requirements will be attempted.

The tunnel-diode current regulator development will be continued.

Development of modulators for the TD oscillator will be continued.

VII. Identification of Key Personnel

Robert D. Gold - Engineering Leader	27 hours
Chester Gurwacz - Engineer	16 hours
Donald E. Nelson - Member of Technical Staff	201 hours
Adam J. Pikor - Engineer	195 hours
Fred Sterzer - Engineering Leader	19 hours
Edgar T. Casterline - Engineer	71 hours

Mr. Casterline was born on March 14, 1934 in New York City. He received his B.S. degree in Chemistry from Manhattan College in 1956. He is currently pursuing a course of study for an M.S. in Physical Chemistry at Stevens Institute of Technology.

From 1956 to 1957, he was employed by the Western Electric Company, as an Analytical Chemist.

He entered the U.S. Military Service in 1957 and was assigned to the U.S. Army Signal Research and Development Laboratory at Fort Monmouth, New Jersey, where he spent two years engaged in work on thin film resistors and capacitors, and thermoelectric cooling devices.

In 1959, he joined the Micromodule group of the RCA Semiconductor and Materials Division where he worked chiefly on the development of thin film resistors and micromodules.

In 1960, he joined the Computer group. His work consisted mainly of research and development on tunnel diodes. One of his main responsibilities was the development on tunnel diodes. He was also responsible for the development of germanium tunnel rectifiers for the "Lightning" project.

In February, 1963, he was assigned to the Industrial Products group, where he is continuing his work on the development of both GaAs and Ge tunnel diodes.

Howard Bertram - Engineer 10 hours

Mr. Bertram studied courses leading to an A.B. degree in Chemistry at Rutgers University College, Evening Division from 1950 to 1959.

From 1950 to 1957, Mr. Bertram was with the U.S. Atomic Energy Commission as a Process Development Chemist. While there, he made significant contributions to the development of a continuous gas-solid reactor.

In 1957, Mr. Bertram joined the RCA Semiconductor and Materials Division, Somerville, N. J., where his assignments have been in the area of device chemistry and fabrication. His major contributions have included the development of a batch-type connector soldering process for the manufacture of alloy junction transistors which significantly reduced the processing cost of this operation, and the development of a process for automatic dot-pressing and alloying which permitted the continuous manufacture of alloyed transistors in strip form. Since October, 1960 Mr. Bertram has been actively engaged in the development of single crystal growth of gallium arsenide. He has done extensive work on vertical growth by the Czochralski method and the pilot line production of gallium arsenide crystal by the horizontal Bridgman technique.

Mr. Bertram has authored papers in the technical literature. He has been issued a U.S. patent.

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This contract is supervised by the Solid State & Frequency Control Division, Electronic Components Department, USAELRDL, Fort Monmouth, New Jersey. For further technical information contact Mr. I. Chase, Project Engineer. Telephone 53-52352.

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AN L-BAND TUNNEL-DIODE OSCILLATOR by D. Nelson, R. Gold and E. T. Casterline. Third Quarterly Progress Report, 1 December 1962 through 28 February 1963, 20 pp., 7 illus. – Contract No. DA36-039 SC-90773
DA Project No. 3A-99-21-002 Unclassified Report

Several 300 ma peak current gallium-arsenide diodes with cutoff frequencies in excess of 9 kmc. were fabricated. These diodes were operated in stripline oscillators and gave power outputs of 24 to 28 mw at 1700 Mc.

Preliminary tests were made on tunnel diode current regulators for the oscillators.

Tests on amplitude modulation of the oscillators were conducted.

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1. Tunnel-diode oscillators

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Gold, R.
Casterline, E. T.

II. U. S. Army Electronics Research and Development Laboratory, Fort Monmouth, N. J.

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